

ANALYSIS OF THE EFFECT OF GRAPHITE MORPHOLOGY
ON THE ELASTIC PROPERTIES OF CAST IRON

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Calculations of elastic constants of cast iron, consisting of an iron matrix with randomly distributed ellipsoidal graphite inclusions of different shape factors, are presented using Eshelby's tensor for a single ellipsoidal inclusion and a differential scheme to take into account finite concentrations. Good agreement with published experimental data is obtained in most cases. Varying the aspect ratio from spheres to discs causes a decrease in the elastic moduli of a factor of approximately three. Implications of this effect, related to assessments of nodularity with elastic constant or ultrasonic velocity measurements, are discussed.

Introduction

Cast irons are largely classified according to their graphite morphology, which is the dominant metallurgical factor affecting their mechanical properties. Gray irons contain interconnected graphite flakes and tend to fracture along the flake boundaries, whereas ductile (or nodular, or spherulitic graphite iron) displays much higher ductility associated with spheroidal graphite. Compacted graphite iron, on the other hand, has properties which are intermediate between gray and nodular iron and is characterized by blunt flakes which are interconnected within cells. The production of compacted graphite and nodular iron requires close metallurgical control to produce the desired morphology and mechanical properties. For this reason, nondestructive techniques to predict mechanical strength are often desirable, especially for parts which are critical for structural integrity. A number of techniques are used in industry for this purpose and have been reviewed (1,2). One of the most useful techniques is the measurement of ultrasonic velocity to determine the degree of nodularity of the graphite inclusions, which strongly affects mechanical properties. Industrial use of ultrasonic velocity for this purpose arises from empirical work which started in the 1960's (for a review, see Ref.3).

The problem of analysing the elastic properties of iron containing graphite inclusions of various shapes was initially treated by Plenard (4) in a simplified manner, which considered only the case of spherical inclusions. More recently, the problem of graphite inclusions with different aspect ratios was analysed by Papadakis et al (5) in a semi-empirical way and by Speich et al (6), who used available theories to treat the extreme cases of spheres and infinitely flat discs.

In the present paper the problem is analysed for randomly distributed graphite inclusions of spheroidal shape having an arbitrary aspect ratio. The theory is based on Eshelby's (7) tensor describing the strain caused by a single inclusion and on a differential scheme for treating the case of finite concentrations. The relation between nodularity and elastic properties is then discussed.

Theory

The theoretical analysis of the effective elastic constants of two-phase materials has been the subject of a great deal of attention. The simplest models assume either uniform strain or uniform stress throughout the composite, giving rise respectively to the Voigt and Reuss averages for the composite elastic moduli, B , E , and G . Both averages yield extreme values which can be very far apart in cases such as the present, where the elastic constants of the inclusions and the matrix can differ by a factor larger than 20. Using variational methods, Hashin and Shtrickman (8) were able to establish rigorous upper and lower values of the moduli which fall within the Voigt and Reuss averages. However, all the above models are insensitive to the detailed shape of the inclusions. Models which take into account the microscopic details of the composite are based on the calculation of the elastic field that surrounds the individual inclusion. The solution for the response of an ellipsoidal inclusion of shape factor p (ratio of the length of the axis of revolution to the length of an axis orthogonal to it) to an homogeneous static strain was given by Eshelby (4). The only assumptions contained in the model are: a) the binder and inclusion material are both elastic, isotropic and homogeneous, b) the inclusion is perfectly bonded to the matrix, c) the inclusion is isolated. The validity of the model being limited to low concentrations, schemes have been proposed to extend the theory to the case of finite volume contents. These have been briefly reviewed recently by one of the

authors (9, 10). In principle, the elastic properties of composites containing randomly oriented inclusions can be obtained from those of aligned composites using a normalized integration scheme. Actually, the calculation is simplified, if the integration over all possible orientations is performed in the zero concentration limit, before allowance is made for larger values of inclusion volume contents. Such an approach was proposed by Boucher (11) in conjunction with the differential scheme (D.S.).

In what follows, we shall use this approach to analyze our data. The exercise appears reasonable in view of our previous work (10), where the D.S. was used with success on composites containing particles of different aspect ratios. Indeed, the results showed that, albeit most schemes were equivalent at low volume contents ($c = 0.12$), the D.S. provided the best description of elastic moduli for larger concentrations. The theory (11) is elegant but the detailed calculations are lengthy and will not be reproduced here. It will be simply stated that, in the limit of very low volume contents, c , the bulk, B , and shear, G , moduli of the composite are expressed as:

$$(B - B_1)/(B_2 - B_1) = cF_1 \quad (1)$$

$$(G - G_1)/(G_2 - G_1) = cF_2 \quad (2)$$

where F_1 and F_2 are fourth rank tensors which are related to B_1 , B_2 , G_1 , G_2 and p (shape factor) and characterize the random orientation. Indices 1 and 2 refer to matrix and inclusion respectively. In order to extend the results of Eqs 1 and 2 to the case of finite concentrations, the composite is progressively built up by adding new particles (D.S.). This is expressed through a system of nonlinear differential equations which must be solved numerically:

$$dB/dc = F_1 (B_2 - B)/(1 - c) \quad (3)$$

$$dG/dc = F_2 (G_2 - G)/(1 - c) \quad (4)$$

Results & Discussion

In our calculations, the matrix was assumed to have elastic constants typical of polycrystalline iron (12), $E_1 = 209$ GPa, $G_1 = 81.3$ GPa and a density of 7.9 g/cm³. The graphite particles are nearly single crystals

in the case of flake graphite, whereas in the case of nodular graphite, the growth is essentially pyrolytic with c axes of the graphite pointing radically in pyramidal regions within the nodules (5). It then seems reasonable as explained in Papadakis (5) to use c_{33} for the compressive modulus normal to the graphite spheres and c_{44} for the shear modulus, resulting in $E_g = 4.41$ GPa and $G_g = 1.5$ GPa. These values are smaller than for polycrystalline graphite by approximately a factor of two. However, since these constants are in all cases approximately twenty-five times smaller than the elastic constants of iron and correspond to approximately 10% of the volume, they have little effect on the final result. The density was taken to be 2.25 g/cm^3 .

Results for the effect of shape factor on the Young's and shear moduli for the case of 11 vol % concentration of graphite are shown in figure 1. It is seen that both moduli decrease by approximately a factor of three as the shape factor is decreased from 1 (spheres) to 0 (infinitely flat discs).

In figures 2 and 3 calculated values of Young's and shear moduli are presented as a function of carbon (graphite) volume content for shape factors of 1, 0.1, 0.03 and 0. The calculations are compared to measurements taken from Speich et al (6). A description of the samples, including volume concentration of graphite, metallographically observed aspect

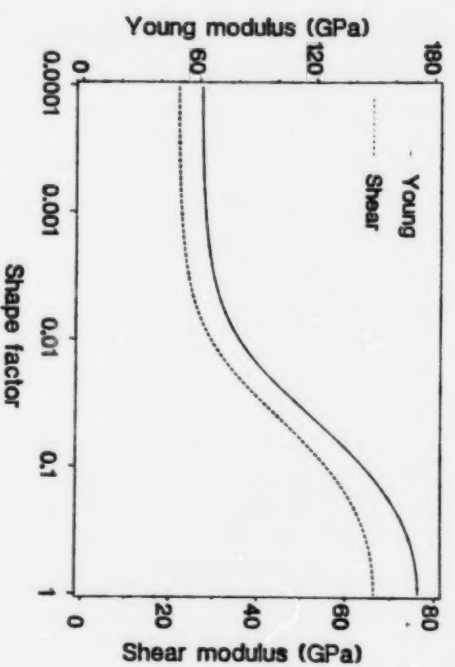


Fig. 1: Variation of Young and shear moduli of cast iron containing 11 vol. % concentration of ellipsoidal inclusions of graphite of different shape factors.

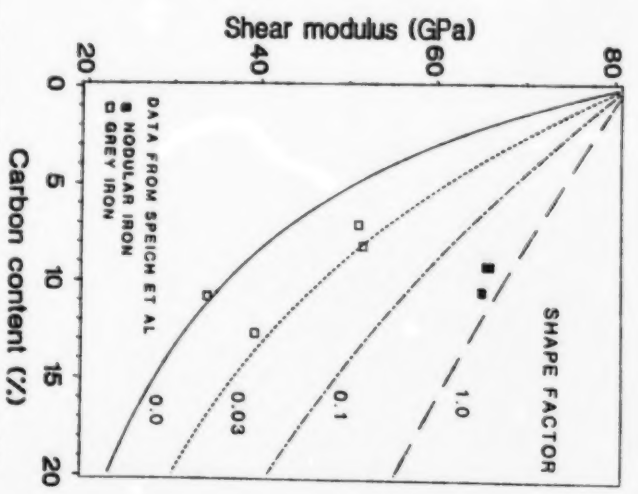
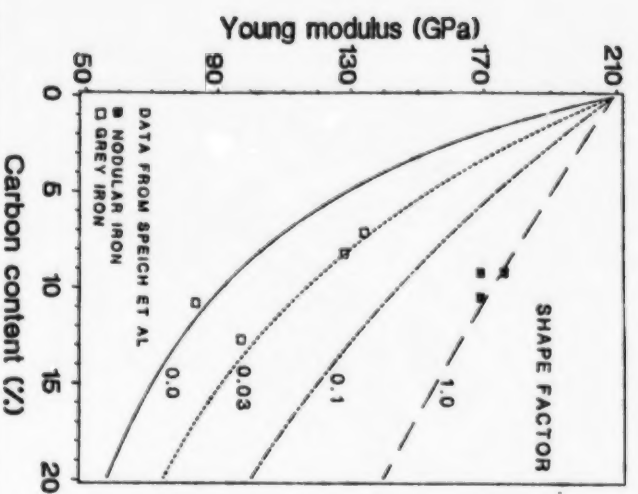


Fig. 2: Young's modulus versus graphite content for graphite of different shape factors. The data points are from ref. 6.

Fig. 3: Shear modulus versus graphite content for graphite of different shape factors. Data points are from ref. 6.

TABLE I

TYPE OF CAST IRON + GRAPHITE Vol. %	AXIAL RATIO (d/c)	MEASURED MODULI ⁺		CALCULATED MODULI	
		YOUNG ⁺ GPa	SHEAR ⁺ GPa	YOUNG GPa	SHEAR GPa
Gray (I)A	8.2	128	51.6	148.4	57.3
Gray (I)B	7.1	134	51.1	154.4	59.6
Gray (II)A	12.7	97.2	39.3	107.9	40.8
Gray (II)B	10.8	83.4	33.8	122.2	46.6
Nodular as cast	9.2	176	66.0	175.2	68.0
Nodular annealed	10.5	169	61.4	170.7	66.2
Nodular normalized & tempered	9.2	169	65.6	175.2	68.0

⁺ from Speich et al

ratio and measured elastic constants, are given in Table 1 together with calculated elastic constants. For nodular iron agreement with theory is within 5%, except for the shear modulus of the sample with 10.5% graphite which deviates by ~ 9%. For gray irons, agreement is within 15%, except for the gray iron II B, where the deviation is ~ 45%.

The small disagreement with theory in the case of nodular iron is probably due to the choice of the elastic constants of the matrix. For gray iron it is seen in figures 2 and 3 that better agreement is obtained for most samples with an inverse shape factor (approximately equivalent to aspect ratio) of $1/p = 33$. The use of a slightly higher inverse shape factor appears to be justified since a metallographic examination of randomly distributed spheroids of inverse shape factor $1/p$ is expected to yield a measured aspect ratio which is smaller than $1/p$. Intersection of an oblate spheroid of inverse shape factor $1/p$ by a plane going through its centre and inclined at 45° to the axis of symmetry will, for instance, yield a shape factor of $\approx \sqrt{2}/p$. One should also take into account the fact that there is a statistical distribution of shape factors, which is not considered presently. The above arguments, however, are insufficient to explain the discrepancy for gray iron II B which requires infinitely flat discs for agreement with theory (figs. 2-3). In this case, effects associated with contiguity, such as discussed by Fiché and Hamel (10), may be important and are outside the scope of the present model.

We shall now analyse the problem of using elastic constant measurements, or ultrasonic velocity to determine the degree of nodularity of nodular cast iron. Nodularity is defined as the percentage concentration of graphite which is spherical. Assuming an overall graphite concentration of 11%, calculations of elastic constants and ultrasonic velocities were obtained for mixtures of spheres and prolate spheroids of different shape factors. Elastic constants were obtained by first introducing the spheres in the differential scheme and then adding the prolate spheroids. Results for the longitudinal ultrasonic velocity are shown in figure 4 for shape factors of the prolate spheroids between .003 and 0.5. It is clearly seen, as expected, that a wide range of ultrasonic velocity can be obtained for a given nodularity level. For this reason it is expected that elastic constant or ultrasonic velocity measurements will give a better indication of mechanical properties than metallographic estimates of nodularity, as is in fact observed experimentally (1,2).

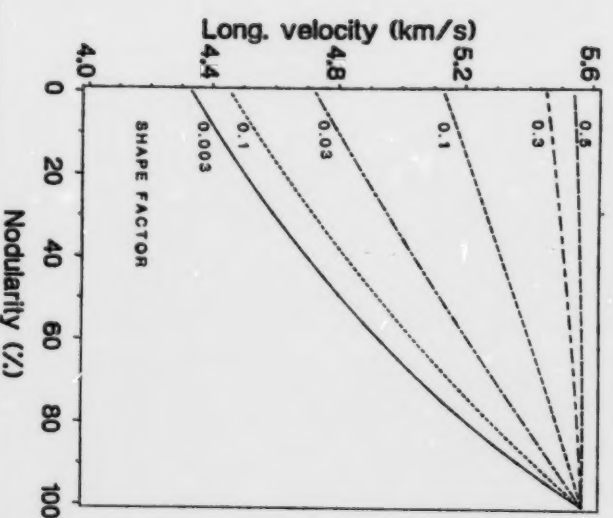


Fig. 4: Calculated values of longitudinal ultrasonic velocity as a function of nodularity for cast iron containing 11% graphite, assuming different shape factors for the non-nodular graphite.

Conclusion

Calculations of the elastic constants of cast iron were presented assuming a pure iron matrix containing randomly distributed ellipsoidal graphite inclusions. The model, which contains no adjustable parameters, is based on a differential scheme for extending Eshelby's solution to finite concentrations and was found to be in reasonable agreement with experimental data published by Speich et al, except for one gray cast iron. Limitations of the model appear to be associated with the fact that all inclusions are assumed to be independent and noninteracting. The relation between nodularity and ultrasonic velocity was found to strongly depend on the aspect ratio of the non-nodular graphite. This limits assessments of nodularity from elastic measurements but not necessarily assessments of quality as it relates to mechanical properties.

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